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Research article

Climate change and potential distribution of potato (*Solanum tuberosum*) crop cultivation in Pakistan using Maxent

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Abstract: The impacts of climate change are projected to become more intense and frequent. One of the indirect impacts of climate change is food insecurity. Agriculture in Pakistan, measured fourth best in the world, is already experiencing visible adverse impacts of climate change. Among many other food sources, potato crop remains one of the food security crops for developing nations. Potatoes are widely cultivated in Pakistan. To assess the impact of climate change on potato crop in Pakistan, it is imperative to analyze its distribution under future climate change scenarios using Species Distribution Models (SDMs). Maximum Entropy Model is used in this study to predict the spatial distribution of Potato in 2070 using two CMIP5 models for two climate change scenarios (RCP 4.5 and RCP 8.5). 19 Bioclimatic variables are incorporated along with other contributing variables like soil type, elevation and irrigation. The results indicate slight decrease in the suitable area for potato growth in RCP 4.5 and drastic decrease in suitable area in RCP 8.5 for both models. The performance evaluation of the model is based on AUC. AUC value of 0.85 suggests the fitness of the model and thus, it is applicable to predict the suitable climate for potato production in Pakistan. Sustainable potato cultivation is needed to increase productivity in developing countries while promoting better resource management

and optimization.

Keywords: climate change; food security; Maxent; *Solanum tuberosum*; species distribution modeling

1. Introduction

Recently, the climatic change has become the cause of concern all over the globe due to unprecedented occurring of extreme weather events. Average temperatures have undergone an increase of 0.85 °C in the last century and it is further predicted to increase to a maximum of 8 °C by 2100 [1]. Less developed nations and low-income communities based on agricultural economy are more susceptible; thus, they are more likely to get impacted with climate change [2].

In coming years, the most suffering communities from climate change will be the ones in Global South, particularly Africa and South Asia [1]. Out of all the other sectors, agriculture is directly affected by global warming and climatic changes due to altered weather conditions [3,4]. The overall global climate change, mainly an increase in temperature has negatively influenced the natural ecosystems and agriculture [5]. There are complex means through which climate change influences agriculture and food production. Alteration in precipitation, extreme heat and drought conditions due to changes in climate are directly responsible for the change in food production patterns [6]. This also results in changes in growth and distribution of incomes with increased demand for agriculture. Future climatic conditions are predicted to be more variable than current climatic conditions as further severe extreme events of heat, droughts, cyclones and floods are expected. These events will be responsible for more fluctuating agricultural yields and thus would lead to food insecurity [7].

Pakistan is an agriculture-based country with an area of about 79.6 million hectares (Mha). The climate is arid and semi-arid. Of all the total area, about 22.1 Mha is suitable for crop cultivation. Of the cultivated land 72% is irrigated through surface and subsurface irrigation system and nearly 28% through rain-fed agriculture. According to World Bank, total agricultural land of Pakistan in 2017 was 202,000 km^2 among top four best agriculture areas globally, but unfortunately this region is experiencing reduction in crop area due to several reasons, for example people migrating to cities, large housing societies, construction of roads and highways, and shortage of water for irrigation. Furthermore, the country has suffered through several natural disasters such as floods, earthquakes, landslides and droughts.

Despite its vibrant agriculture-based economy, Pakistan is more likely to be impacted with food shortage and agricultural down fall [8,9]. Thus, lack in agricultural output will be detrimental and a major cause of food insecurity risk that might impact the health and economy in future [10]. Pakistan is ranked poorly on Global Hunger Index that emphasizes the seriousness of the issue [11]. According to estimates, around 127 million people in Pakistan suffer from food insecurity [12]. Mostly children are malnourished and live below poverty line. With such depleting figures, extreme weather events affecting major food crops of Pakistan including wheat, maize, rice and potato, is extremely alarming.

Potato (*Solanum tuberosum*) can grow in warmer as well as cooler climates, however it cannot thrive in harsh climatic conditions such drought, high temperature and high humidity [13]. In many countries Potato is grown as a major crop under different climatological zones, such as temperate regions, the sub-tropics and tropics, under very different agro-ecological conditions, lowlands and highlands. Presently, the potato crop is cultivated in about 130 countries and there are nearly 5000 potato varieties worldwide [14]. With regard to the global food consumption, potato ranks third as an important non-grain crop. FAO has declared potato as the food security crop because it provides nutritious food to poor and hungry where the world is facing issues with food accessibility [15]. After wheat, rice, and maize, potato is now the fourth most important global food crop due to better yield and high nutritive value. Potatoes are a good source of carbohydrates, vitamins, and minerals. Vitamins includes niacin, thiamin, riboflavin and vitamin C [16]. The economically significant part of the potato is tuber, site for storage of carbohydrates and consists of about 77% water, 20% indigestible carbohydrate [14].

China is the biggest producer of potatoes worldwide, with about one third of the world's potatoes produced in China and India. According to FAO estimates, in 2019, over 370 million metric tons of potatoes were produced worldwide, a substantial increase from a production volume of 333.6 million tons in 2010. However, this region is ecologically fragile, and agricultural production is vulnerable to climate change [17]. Hinjmans [18] studied the effect of climate change on global potato production using LINTUL simulation model. Potential yields were calculated for current (1961–1990) and projected (2010–2039 and 2040–2069) conditions. The study revealed that at high latitudes, global warming will likely lead to a shift of the location of potato production. Model predicted changes in potato yield to be relatively small, and sometimes positive. In the tropics, where there is little temperature change during the year, there is not much scope for adaptation of potato production. In India and Bangladesh where potato is a winter crop already grown in the coldest season, climate change might reduce potato yield. It is predicted that an overall fall of 9.56% at national level if needed steps are not taken to mitigate the effects of climate change [19].

Potatoes are grown over a large area of Pakistan with the production of roughly 4.1 million tons. They are largely grown in the central and northern plains of Punjab and KPK. Some parts or districts of Baluchistan in west supporting the production of potato, include Pishin, Killa Saifulla, Kalat and Gilgit district in Gilgit-Baltistan. Potato in Pakistan is not yet being produced to its maximum capacity as compared to neighboring India and Bangladesh [20] however, to assess the impact of climate change on potato crop in Pakistan, especially in the areas which are rain fed, it is essential to analyze its distribution under future climate change scenarios. This can be achieved through the use of various modeling techniques. Species Distribution Models (SDMs) use a combination of numerical tools with species presence data along with various environmental factors. Maxent (Maximum Entropy) is one such species distribution model which forecasts the distribution of a given species using only its presence data [21], capable of modeling crop suitability [22] and provides the most precise distribution function based on best entropy [23,24]. The model has been widely used all over the world to predict changes in the geographical distribution of species under climate change [13,25]. Based on the wide use of Maxent for species distribution, this study was designed with the main objective to predict potato crop distribution across Pakistan by comparing two climate change scenarios RCP 4.5 and RCP 8.5 with two CMIP5 models.

2. Materials and methods

2.1. Study area

Pakistan, with a latitude of 30.3753° N and longitude of 69.3451° E, is the study area of this research work. Pakistan is located in South Asia with an area of about 881,913 km^2. It is bordered by countries like India, Afghanistan, Iran and China. It also has coastline along Arabian Sea in the South. Pakistan is a country with a diversified temperature and precipitation patterns. Very high altitudes modify the climate in the cold, snow-covered northern mountains; temperatures on the Balochistan plateau are somewhat higher (Figure 1a). Along the coastal strip, the climate is modified by sea breeze. In the rest of the country, temperatures reach great heights in the summers. Surface-water resources in Pakistan are based on the flows of the Indus River and its tributaries. Climate is not uniform over the Indus river basin. It varies from subtropical arid and semi-arid to temperate sub-humid on the plains of Sindh and Punjab provinces to alpine in the mountainous highlands of the north. Potatoes are mostly cultivated in Pakistan where irrigation is available. Punjab leads in potato production with 83% of total production followed by KPK with 10%. Baluchistan contributes 6% to the potato production whereas only 1% potatoes are cultivated in Sindh.

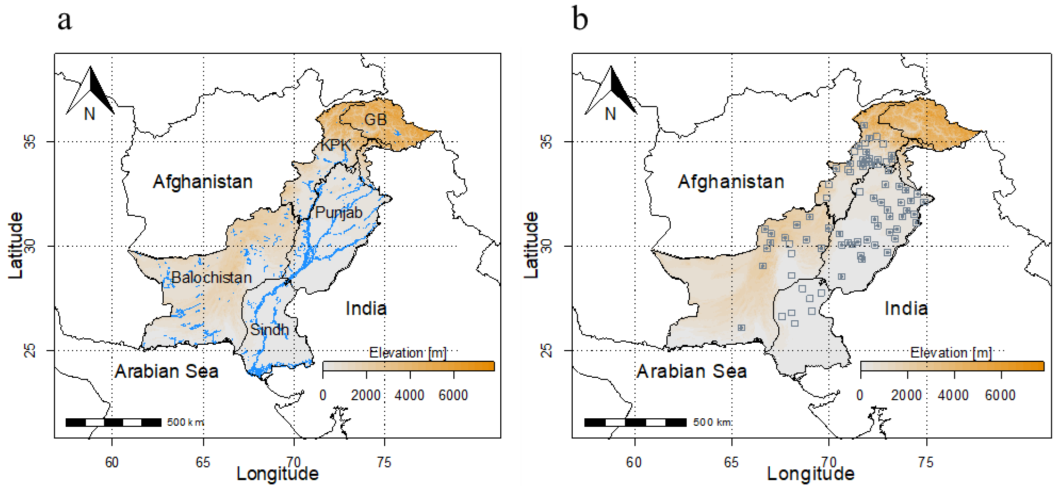

Figure 1. a: Study area with alatitudinal gradient and major river system. b: Study Area with Potato Presence Locations, where the open grey squares show current potato cultivation and the closed grey squares show the final data points selected for Maxent.

2.2 Occurrence data

Collection of occurrence records for *Solanum tuberosum* was done primarily from report of Statistical Bureau of Pakistan [26]. Unpublished data was taken from Potato Research Centers in various cities, Sahiwal, Sialkot and Murree in Punjab province in December 2018. GPS points were gathered during field visits to Abbottabad, Mansehra and Feteh Jang in KPK province. The data gathered from these sources was further processed, where areas with high potato yield were considered and areas with low potato yields were discarded. This was done by calculating average of production/area for the years 2005–2012 and data points for locations with yield (production/area) above average were considered for input in the Maxent model. To correct for clustered occurrence records that affect SDM predictions, we used a raster grid size of 0.05 degrees of latitude, which are equivalent to about 5 kilometers square. This method randomly selects a single point from each grid square. The total occurrence data points selected were 58 (Figure 1b).

2.3 Environmental data

19 Bioclimatic variable layers (BIO 1 to BIO 19) (Table 1) for two models CCSM4 and MPI-ESM-LR were downloaded from WorldClim website (https://www.worldclim.org/) using R-program [27]. This website provides current (1960–1990), high resolution WorldClim climate data and future climate projections from global climate models (GCMs) for four representative concentration pathways (RCPs).

Table 1. Caption list of bioclimatic variables derived from monthly temperature and precipitation values in order to generate future predictions.

Code	Bioclimatic variables name
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp-min temp))
BIO3	Isothermality (BIO2/BIO7) (*100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

These models were selected to explain variation in model outputs, and any uncertainty in single model predictions. MPI-ESM-LR is low-bias and high-sensitivity model and has least interdependency to CCSM4 [28]. The future projections selected for the analysis along with current bioclimatic layers, included two climate change scenarios RCP 4.5 and RCP 8.5. RCP 4.5 represents a future in which some collective action is taken to limit GHG emissions, with global annual average temperatures increasing 2.4 ℃ by 2100. RCP 8.5 is closer to a scenario in which no actions are taken to reduce emissions, and global annual average temperatures increase 4.3 ℃ by 2100. The average prediction by these climate models is that annual average temperatures in South Asia will increase 1.6 ℃ by 2050 under RCP 4.5, and 2.2 ℃ under RCP 8.5. As these increases are relative to 1981–2010 conditions [29], hence these two RCPs were selected for the analysis. Each layer had a spatial resolution of 30sec and was converted to ASC format in R-program as required by Maxent [30]. Additional covariates were also downloaded from FAO website including Soil type and Irrigation (from FAO.org). Digital Elevation Model Data was downloaded from SRTM DEM 30 m resolution (https://gisgeography.com/free-global-dem-data-sources/). These covariates were incorporated in the analysis along with the bioclimatic layers to evaluate their impact on crop distribution.

2.4 Maxent modeling and evaluation

Occurrence data file in "txt" format along with 19 current bioclimatic variable and covariates (soil type, irrigation and elevation) ASCII grid files with same resolution were incorporated in R-program The R package dismo [31] was used to run Maxent model. Maxent has two main modifiable parameters: (1) regularization multiplier and (2) feature classes. The regularization multiplier sets how focused or closely-fitted the output distribution is–a smaller value than the default of 1.0 will result in a more localized output distribution that is a closer fit to the given presence records. A larger regularization multiplier will give a more spread out, less localized prediction [32]. The "regularization multiplier" parameter was set to 1 for this study. "Feature class" is an expanded set of transformations of the original covariates [33] which constrains the computed probability distribution. The available feature types include linear, quadratic, product, threshold, and hinge [30]. The selection of feature class is related to the number of species occurrence points. By default, the program restricts the model to simple features if few samples are available [33]. Model generally uses linear feature; quadratic feature is used with at least 10 samples; hinge is used with at least 15 samples; threshold and product with at least 80. Combinations of all feature classes are usually used as default [30,33,34]. 1000 Background points were randomly selected all over the study area to generate the suitable area maps. 5-fold cross-validation method was used which means Maxent randomly partitioned the occurrence data into five independent sets and repeated the model building process five times. Thus, the maps for suitable habitat for current climatic conditions were generated. Same procedure was repeated for future scenarios (RCP 4.5 and RCP 8.5) with future bioclimatic variable layers but the covariates were kept constant. Maps for future scenarios were generated and suitable areas for potato production were calculated for current climate and future scenarios. Maps for suitable area for all provinces were generated. Model was evaluated on the basis of area under receiver operating characteristic curve (AUC) which is a threshold-independent statistic commonly used to evaluate species distribution models. Maxent calculated AUC values for both the training and test data.

2.5 NDVI based validation

Satellite images of Landsat 8, level 1 for October and November 2018 were downloaded from USGS website. The images used to validate the exact locations of potato production using NDVI range. For this reason, band 4 and band 5 from all the files were extracted and separated. After mosaicking and removal of cloud cover further atmospheric correction was done and thus, NDVI for the final product was calculated. The final mosaicked file was further clipped by masking using R-program. After processing of the files, classification was done to get the locations of potato using NDVI range 3–6 extracted from literature. Map for NDVI range for potato was generated and thus validation was done against the current distribution maps.

3. Results

Potato climatic distribution is dependent on a certain low temperature range, availability of enough water, soil pH and fertile soil that supports its growth. These conditions might change in future due to changing climatic scenarios thus leading to the reduction in suitable area for potato cultivation.

3.1 Current potato distribution

Using accumulative output of the real outcomes from the Maxent model [35], raw maps were generated which showed highly suitable, moderately suitable, least suitable and unsuitable climate areas for potato production in Pakistan (Figure 2a).

NDVI based map (Figure 2b) validated the presence locations of the potato in field-based map (Figure 1) except for some area in Sindh Province. These areas might have some other crops or vegetation such as Maize (NDVI Range 0.25–0.75) which falls under the same broad range of potato and widely grown in Sindh under the same weather conditions [36].

Another approach used for the evaluation of model was by defining thresholds. In this approach, threshold selection is done for the establishment of the locations that are considered suitable and non-suitable for vegetation. Minimizing the specificity and maximizing the sensitivity are the key criteria that define the thresholds [37,38]. The threshold map (Figure 2c) was generated to simplify the output of Maxent model and present it in binary form (suitable and non-suitable climate locations). The area calculated as suitable climate for potato production under current scenario was about 265,016 km^2. Punjab province was found to be the most suitable area to grow potato. The suitable area for Punjab was about 152,411 km^2, followed by KPK with an area of 56,392 km^2. The share of Baluchistan and Sindh was about 42,509 km^2 and1239 km^2 respectively. Suitable area under the territory of Gilgit Baltistan was calculated to be about 5,534 km^2. Out of all the provinces, Sindh had the least suitable climate to grow potato as the temperature and climate of Sindh even in winters is not suitable for Potato cultivation.

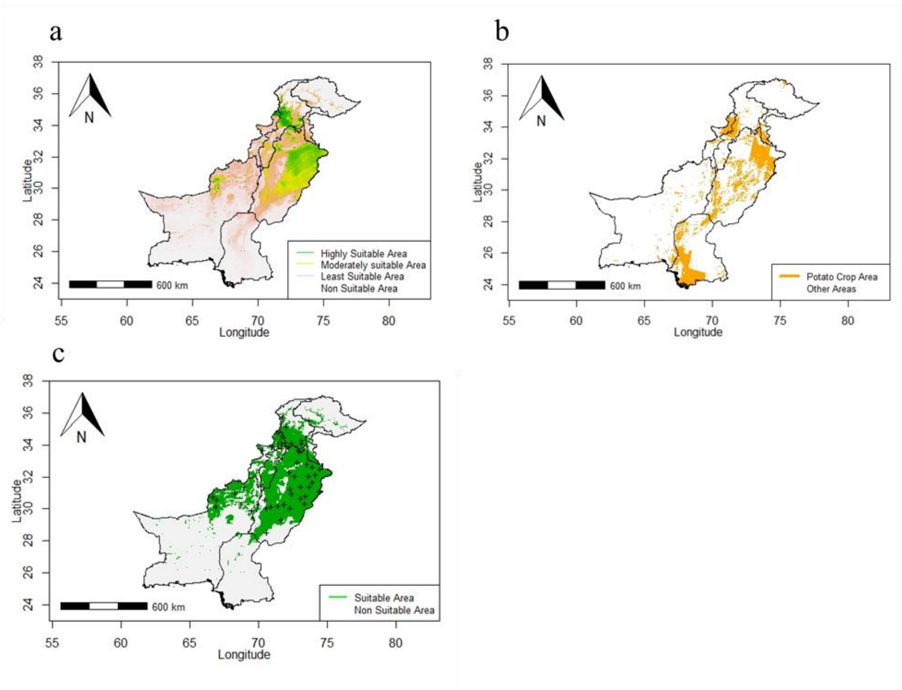

Figure 2. a: Current climate raw value map showing suitable areas for potato production in Pakistan. b: NDVI based thresholding map for potato crop area in Pakistan. c: Final threshold map showing only suitable climate for potato production in Pakistan.

Jackknife test was used to estimate the variable importance. The jackknife test is shown by a bar graph of pink and blue bars with red vertical dotted line (Figure 3). The size of pink bar denotes the score with one of the climatic indices; the length of the bar indicates the importance of that variable, more the length, more important is that variable. After running Jackknife for variable importance, the most important variables were found to be isothermality, soil type, mean temperature of the driest quarter, precipitation of wettest quarter and annual precipitation.

Figure 3. Legend Jackknife test of variable importance for current distribution of potato where the size of red bar denotes the score with one of the climatic indices. The length of the red vertical dashed line represents the total score for simulating the distribution of potato using all the selected potential climatic indices and the blue bar represents the score of a model created with the remaining indices.

3.1.1 Model evaluation

Assessment and evaluation of Maxent model can be done using area under the receiver operating characteristic (ROC) curves (AUC). ROC is plotted after plotting the sensitivity values (True positive rate) on y-axis and 1-specificity values (false positive rate) on x-axis (Figure 4). The area under the curve (AUC) measures the overall accuracy of the model. Higher AUC values depict better performance of the model and AUC lower than 0.5 suggests no discrimination [37]. If AUC values are more than 0.78, then the model has performed well [39]. In case of current distribution of potato using Maxent, the results of AUC 0.85 showed that the model performed well, and results showed strong likelihood of crop distribution.

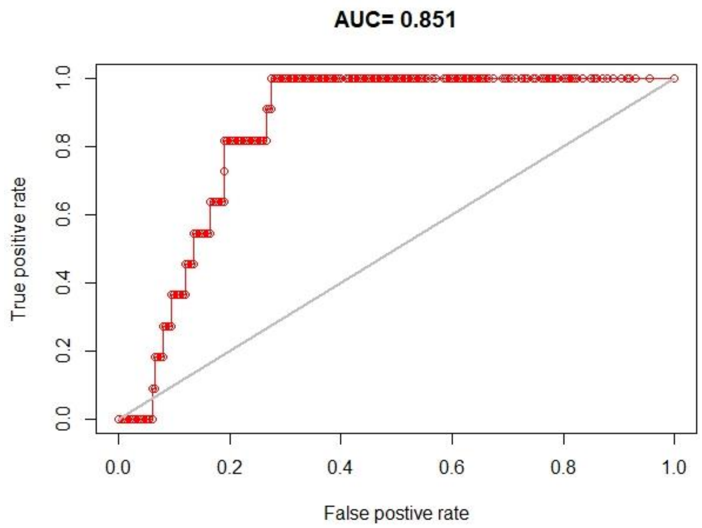

Figure 4. Area Under Curve (AUC) for current distribution describing the relationship between the proportion of observed presences correctly predicted (True Positive Value) and the proportion of observed presences incorrectly predicted (False Positive Value).

3.2 Future potato distribution

Future CMIP5 models, CCSM4 (Model 1) and MPI-ESM-LR (Model 2) were used for this study. Future distribution of potato was predicted for 2070 under RCP 4.5 and RCP 8.5. The results for RCP 4.5 showed a slight decrease in the suitable area for potato cultivation in comparison with the area shown in current distribution. In model 1 (Figure 5a) the suitable area calculated was about 237,132 km^2 where the area suitable in Punjab was found to be 149,193 km^2 followed by KPK which was 43,053 km^2. Suitable area in Baluchistan was predicted to be 35,300 km^2 and in Sindh it was predicated to be about 518 km^2. Gilgit Baltistan had about 3,556 km^2 area suitable for potato production. In model 1 the suitable area reduction for RCP 4.5 was about 10.5% for whole Pakistan. For model 2 (Figure 5b) the suitable area calculated was about 252,449 km^2 in which suitable area in Punjab was found to be 145,200 km^2 followed by KPK which was 54,390 km^2. Suitable area in Baluchistan was predicted to be 36,602 km^2 and area in Sindh was about 27,23 km^2. Gilgit Baltistan had an area about 6,193 km^2. In model 2 the suitable area reduction for RCP 4.5 was about 4.7% as compared to the current area.

In RCP 8.5 there was a drastic decrease in the suitable area for potato cultivation. The suitable area calculated was about 76,608 km^2 in model 1 (Figure 5c) in which suitable area in Punjab was found to be 47,411 km^2 followed by KPK which was 210,257 km^2. Suitable area in Baluchistan was predicted to be 46,89 km^2 and in Sindh, it was found to be only 29 km^2. Gilgit Baltistan had about 1,032 km^2 area suitable for potato production. For RCP 8.5 the suitable area reduced was about 71% with respect to the current suitable area. In model 2 (Figure 5d) the suitable area for whole country was about 154,598 km^2. Area found suitable in Punjab was 106,086 km^2 followed by KPK which was 31,440 km^2. Suitable area in Baluchistan was predicted to be 11,183 km^2 and area in Sindh was predicated be only 58 km^2. Gilgit Baltistan had about 3,460 km^2 area suitable for potato cultivation. For RCP 8.5 the suitable area reduced was about 55.5% with respect to the current suitable area.

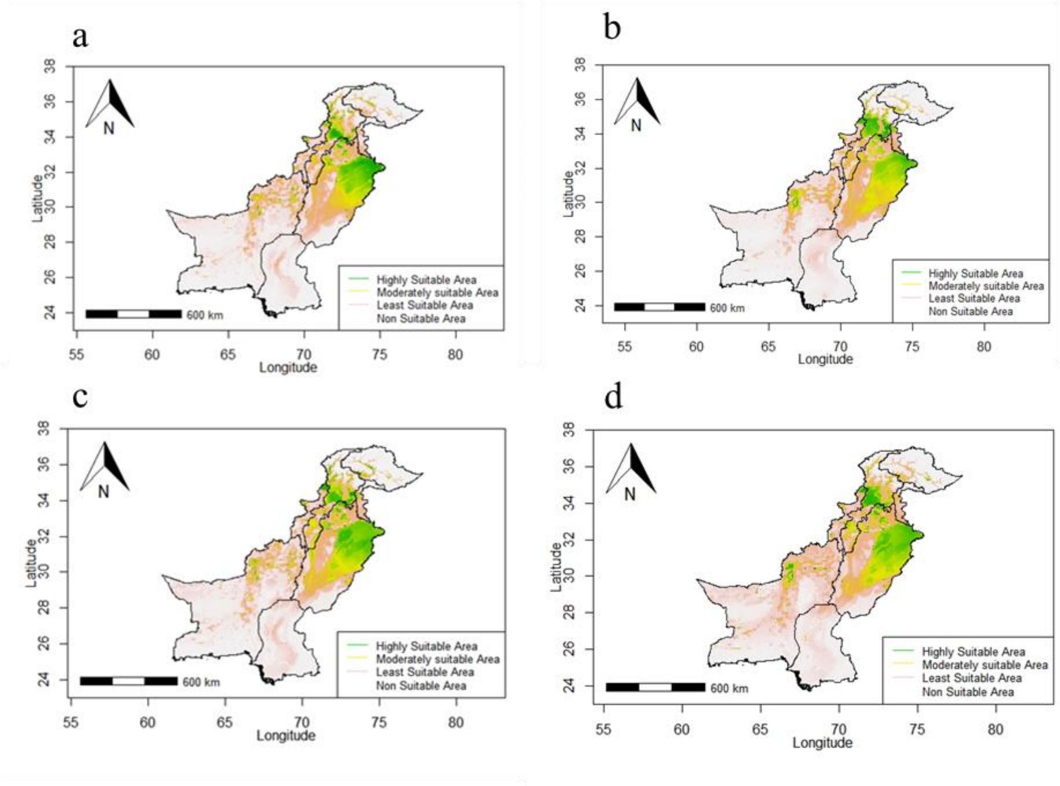

Figure 5. Raw maps for future 2070 climatic distribution of potato in Pakistan. a and b: CCSM4 predictions for RCP 4.5 and RCP 8.5. c and d: The predictions for MPI-ESM-LR for RCP 4.5 and RCP 8.5.

4. Discussion

Potato is one of the basic food crops grown in Pakistan. It is very important to see its future distribution in order to cope with future food insecurity. Maxent modeling was used to analyze its future distribution with two future models and both models predicted decrease in the suitable area for Potato cultivation in 2070. The predicted highly suitable cultivation regions were located mainly in Punjab and KPK. In model 1 the suitable area reduction for RCP 4.5 was about 10.5% and for RCP 8.5 the suitable area was reduced was about 71% with respect to the current suitable area. In model 2 the suitable area reduction for RCP 4.5 was about 4.7% and for RCP 8.5 the suitable area reduced was about 55.5% with respect to the current suitable area. Important environmental factors shaping suitable habitat of Potato for current climate included isothermality, soil type, temperature of driest quarter, precipitation of wettest quarter and annual precipitation.

In this research, modeling of the current and future distribution of Potato cultivation in Pakistan was done. Area Under the Curve value of 0.85 for current distribution indicated the robustness of the model [40]. Under the current and future scenarios, classification based on potato production for the highly suitable, moderately suitable, less suitable and non-suitable area was done. The findings for the current scenario are supported by the other studies [23] for the cultivation of Ceylon Spinach and by [24] for the cultivation of Vegetable Roselle in which the results showed that Maxent Modeling Approach can be used as a tool to study the climate suitability of different vegetable crop species.

The results for the future distribution of *Solanum Tuberosum* coincided with the findings in the literature [13,41–44] in which a temperature sensitive species underwent drastic decrease in the suitable habitat under the RCP 8.5 for year 2070 and suggested that one of the key factors shaping the distribution of the species was annual precipitation [43]. Another factor that was very important in the growth of potato was soil type, without suitable soil type and pH range, the growth of the species was not possible in any scenario. In a study on one of the mushroom species, *Tricholoma matsutake* was found to be highly dependent on the suitable soil type and no yield was predicated without favorable soil conditions even though the climate and topography were in the favor of its production [13].

With sufficient water supply, studies through free-air CO_2 enrichment systems (FACE) have reported a yield increase in potatoes [45–47]. Many studies are going on to analyze the interaction between CO_2 increase and warmer temperatures in field crops [46]. Currently, only modeling provides some insight about their combined effect on potato growth and environment. However, similar results were found as this study with drastic decrease in potato yield using RCP8.5 [48].

5. Conclusions

Based on current and future potato cultivation distribution model predictions, the study showed a decline in Potato yield in both RCP 4.5 and RCP 8.5 climate change scenarios. The magnitude of uncertainty for RCPs and GCMs increases towards the end of the century. Pakistan is going to experience large year-to-year climate variability causing low yields in some seasons. Climate change enhances variability; however, uncertainty is also large, partly due to GCM scenarios used for this region and partly due to variability in growing conditions. Pakistan, that most depend on potato production for food security, is also a region least able to invest in agriculture and is the hardest hit by climate change impacts. Developing strategies and tools to comprehensively understand the impact of climate change and evolve possible adaptation measures in horticultural crops is less understood. Present research can be used for the future assessment of other non-grain crops and thus the estimates can help to generate more yields by adopting ways to enhance growth and cultivation of similar crops in the future when food insecurity will be rather challenging. Without better projections of crops in the future, there would be more chances of food shortage and famine.

Acknowledgments

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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